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Super Thin Ultra-Light Posttensioned Flat Plate Floor Systems for Affordable Urban Housing

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Introduction and Research Motivation

Median housing prices in many big cities are well above the national average. In Boston, New York City, Washington DC, Denver, and Seattle median housing prices are between $300k and $400k. Cities in the west coast such as San Francisco, Los Angeles and San Diego feature median housing prices that are well above $400k (Clear Capital 2015). Accordingly, urban housing is still not affordable for many people. The combinations of high construction cost due to the inability of traditional materials to provide efficient and sustainable structures and land use regulations create challenges for investors who are trying to provide affordable housing and maximize profit. To address these issues, this research will present several super thin lightweight posttensioned floor systems that can be used in midrise and high-rise construction to accommodate the growing demands for *affordable* urban housing while complying with existing regulatory limits on building *height* (Fig. 1).

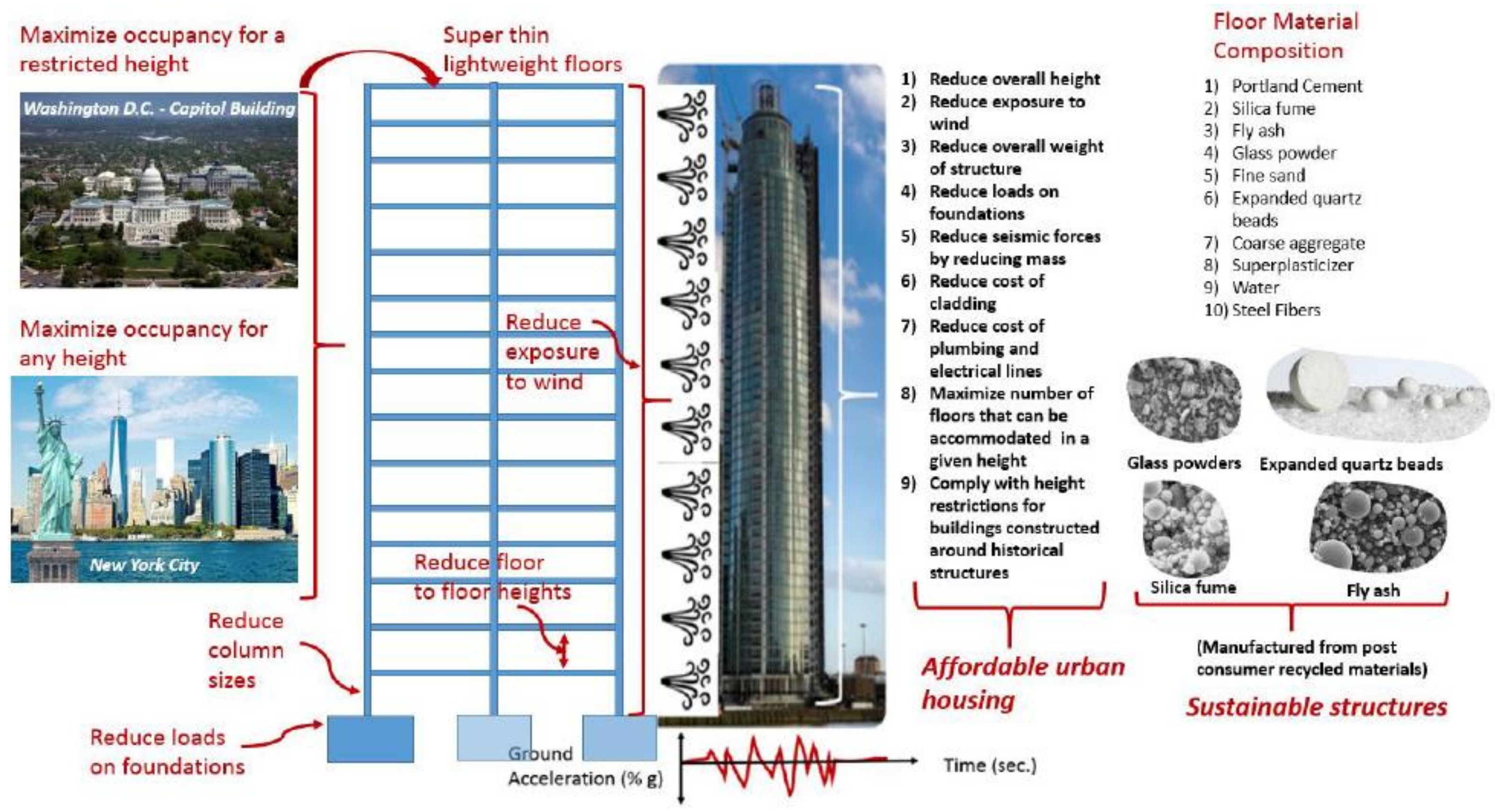


Fig. 1 Benefits of super thin lightweight floor systems

Technical Objectives

The objective of this research is the development of super thin ultra-light posttensioned flat plate floor systems by using high performing ultra-light cementitious composites that lead to slender, sustainable structures to remove the limitations imposed by commodity materials on midrise and high rise construction. This objective will be achieved by investigating the full-scale behavior of these super thin floor systems using high fidelity finite element analyses in terms of flexure, punching shear, long term deflections, and vibrations.

Research Approach

To demonstrate the benefits of super thin ultra light posttensioned floor systems, a typical floor plan featuring 3 bays with 20 ft by 25 ft maximum bay sizes was designed using traditional and high performance concrete mixes. The design for stresses at service, flexure and punching shear was conducted using hand calculations according to ACI 318-14. Load demands were determined using a column strip approach and were later verified with those obtained from linear elastic finite element analyses software (Ram Concept). Vibration performance was quantified using linear elastic dynamic analyses. Long term deflections were determined using linear elastic analysis using cracked sections properties. Creep was considered using the age adjusted effective modulus approach.

Material Properties

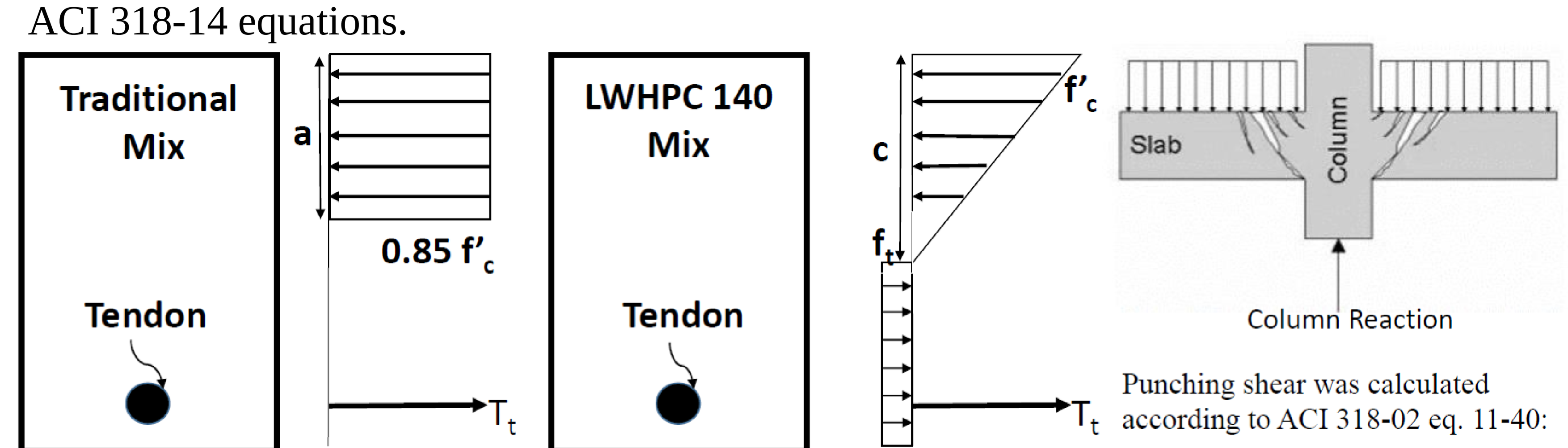
The material properties for the traditional concrete mix as well as high performance concrete mixes are presented in Table 1. The HPC mixes feature unit weight as low as 116 pcf and compressive strength as high as 21 ksi. Additionally, tensile strengths are as high as 2.91 ksi.

Table 1. *Material properties at 28 days*

Mix	Unit Weight (lb/ft^3)	f'_c (ksi)	Tensile Strength (f_t) (ksi)		E (ksi)	v
			First crack (f_{tm})	Ultimate load (f_{tu})		
Traditional	145	4	0.38	0.47	2900	0.20
Ductal	156	21	1.62	2.61	8167	0.17
VHPC	148	17.3	1.32	2.92	5355	0.15
LWHPC140	129	13.3	1.16	2.64	4326	0.18
LWHPC130	122	10.7	0.9	2.08	3992	0.17
LWHPC120	116	9.2	0.85	1.71	3356	0.19

Flexure and Punching Shear

Flexural strength of the floor featuring the traditional mix was quantified using Whitney's stress block. Whereas the flexural strength of the floors with the HPC mixes was calculated using experimentally obtained stress strain curves. Punching shear strength was based on ACI 318-14 equations.



Design stress in tendon was calculate according to ACI 318-02 eq. 18-5:

$$f_{ps} = fpe + 10{,}000 + \frac{f'_c}{300}\rho_p \le \begin{cases} f_{py} = 0.85 f_{pu} \\ f_{se} + 30 \end{cases}$$

f_{ps}=stress in prestressing steel, *psi*
f_{pe}=compressive stress in concrete due to effective prestress forces, *psi*
f'_c=compressive strength of concrete, *psi*

f_{py}=yield strength of prestressing steel, *psi*
f_{pu}=tensile strength of prestressing steel, *psi*
f_{se}=effective stress in prestressing steel, *psi*
ρ_p=ratio of $\frac{A_{ps}}{b_w d}$

Note: The validity of these equations for HPC mixes is the focus of future work.

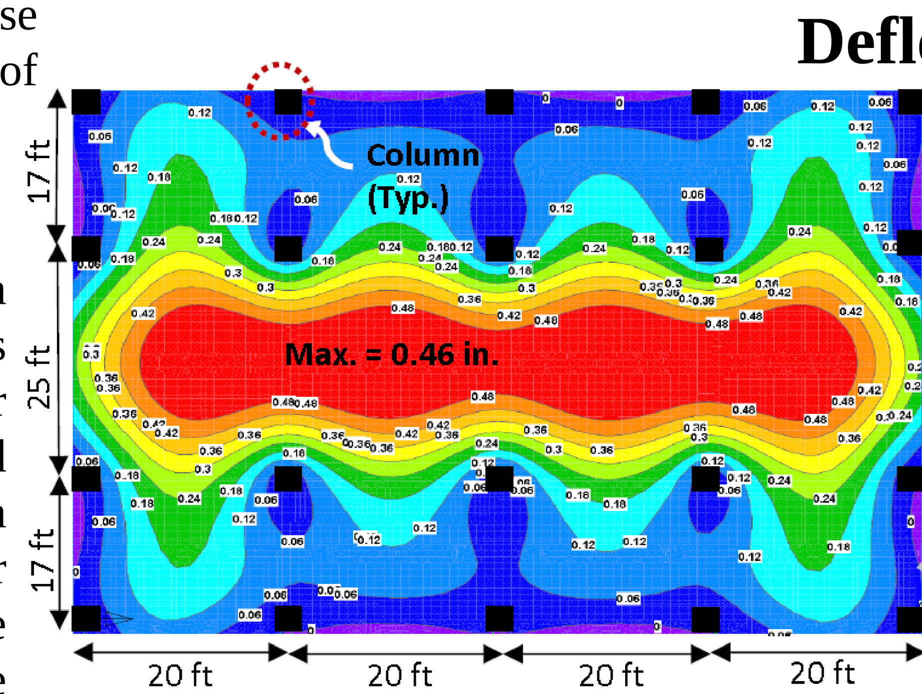
Punching shear was calculated according to ACI 318-02 eq. 11-40:

$$v_u = \frac{V_u}{A_c} + \frac{\gamma_v M_u}{\frac{J}{c}}$$

v_u= maximum factored two-way shear stress, *psi*
V_u= factored shear force at section, *lbs*
A_c= area of concrete section resisting shear transfer, in^2
γ_v= factor used to determine the fraction of M_{sc} transferred by eccentricity of shear at slab-column connections
M_u= factored moment at section, *in-lbs*
J_c= property of assumed critical section, in^4
c = distance from extreme compression fiber to neutral axis, *in*

Fig. 2 Flexure and Punching Shear Behavior

Deflections



Live load deflection contours (LWHPC140)

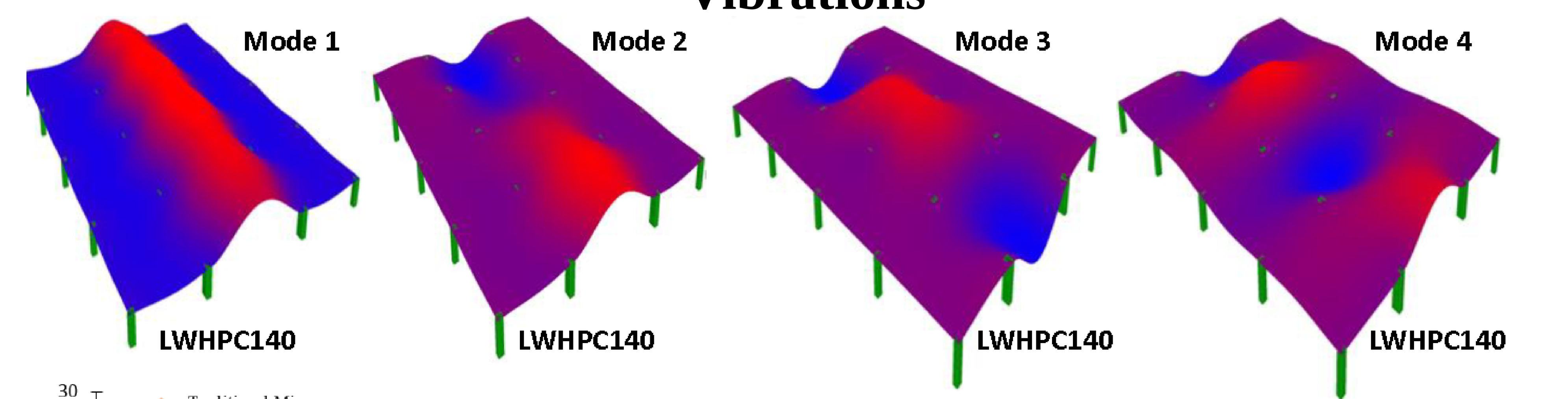
Fig. 3 Deflections

Table 2. *Deflections*

Mix	ΔLL	Limit [L/360]	Ratio	ΔL.T.	Limit [L/240]	Ratio
Traditional Mix	0.125	0.833	0.150	0.397	1.25	0.317
Ductal	0.246	0.833	0.295	0.910	1.25	0.728
VHPC	0.377	0.833	0.452	1.087	1.25	0.869
LWHPC 140	0.458	0.833	0.549	1.159	1.25	0.927
LWHPC 130	0.496	0.833	0.595	1.268	1.25	1.014
LWHPC 120	0.589	0.833	0.707	1.468	1.25	1.175

Conclusions: Live load deflections for all five HPC mixes are smaller than the code limit. The sum of long term deflections due to sustained loads and live load deflections is smaller than the code limit assuming non structural components not likely to be damaged by large deflections for three of the HPC mixes. The floors with LWHPC130 and LWHPC120 mixes exhibit long term deflections that are slightly over the code limit. However, these deflection estimations are conservative because RAM Concept ignores the tensile behavior of the HPC mixes.

Vibrations



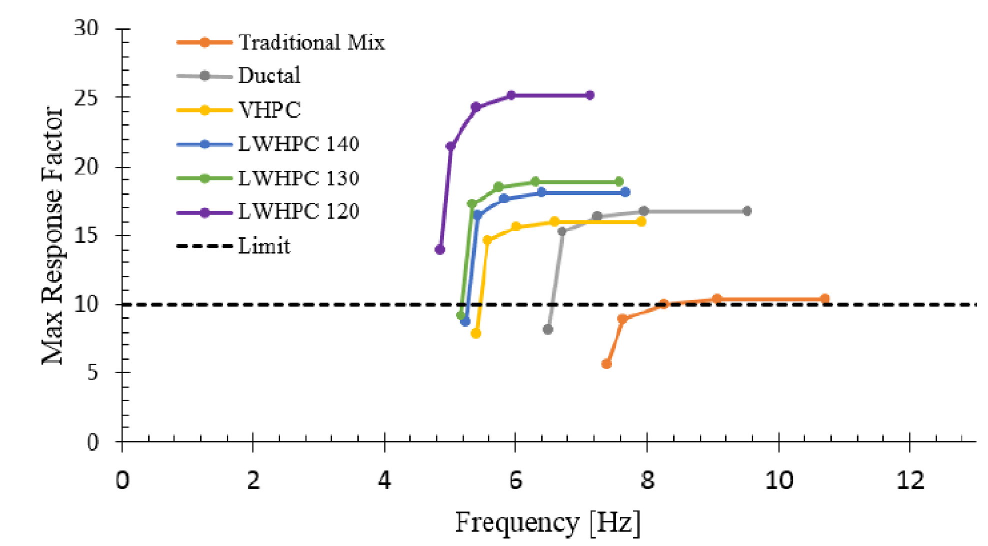


Fig. 4 Vibrations

Conclusions: The floors with the high performance concrete mixes exhibited higher vibrations than typically adopted limits. However, Ram Concept ignores the contribution of the tensile strength of concrete, which is significant for the HPC mixes. A more accurate of vibration performance will be conducted using nonlinear dynamic analysis in Abaqus and the behavior is expected to be improved significantly.

Conclusions and Recommendations for Future Work

The utilization of HPC mixes results in floor weight and floor thickness reductions as high as 50% and 38%, respectively. Additionally, gravity loads demands on columns and walls, and seismic load demands on lateral load resisting systems are significantly reduced.

Table 3. *Performance and benefit of super thin slabs with HPC*

Floor Configuration	Floor Thickness (in.) [% reduction]	Floor Weight (psf) [% reduction]	Demand/Capacity		
			Net Tensile stresses at service [f_n/f_t]	Flexure stress at ultimate [$M_u/\varphi M_n$]	Two-way shear [$V_u/\varphi V_n$]
Traditional	6.5 [0]	81 [0]	0.53	0.85[a]	0.92[c]
Ductal	4.0* [38]	54 [34]	0.52	0.47[a]	0.72[c]
VHPC	4.0* [38]	51 [37]	0.60	0.54[b]	0.73[c]
LWHPC140	4.0* [38]	45 [45]	0.60	0.52[b]	0.79[c]
LWHPC130	4.0* [38]	42 [48]	0.73	0.60[a]	0.90[c]
LWHPC120	4.0* [38]	40 [50]	0.73	0.63[b]	0.88[d]

[a]At column centerline span 2, [b]At midspan 2, [c]At interior column, [d]At exterior column
*Minimum thickness was limited to 4.0 in. because of unknown performance during a fire event.

The behavior of the super thin floors was investigated using linear elastic finite element analyses and hand calculations using strength prediction equations based on ACI 318-14. Full scale nonlinear finite element analyses will be employed in the future to capture the true behavior of the slabs. These investigations will consider the contribution of concrete in tension after cracking occurs, which is expected to reduce long terms deflections and improve dynamic behavior in terms of vibrations.

Acknowledgements

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